Multi Mirror System for an Illumination System

The invention relates to a multi-mirror-system for an illumination system, especially for lithography with wavelengths ≤ 193 nm comprising an imaging system.

EUV-lithography constitutes one of the most promising candidates for next generation lithography. The evolution of semiconductor fabrication demands reduced feature sizes of 50 nm and beyond. This resolution is obtained by the application of a short wavelength of 13.5 nm and moderate numerical apertures of 0.2 to 0.3. The image quality of the lithography system is determined by the projection optics as well as by the performance of the illumination system. Illumination system design is one of the key challenges of EUV lithography. In today's lithographic systems, the illuminator has to deliver invariant illumination across the reticle field. For EUV, several additional requirements have to be addressed.

EUV imaging systems need to be realized as reflective optical systems. For this reason, an unobscured pupil and a highly corrected image field can only be achieved in a small radial range of the image. Hence the field shape is a ring-field with high aspect ratio of typically 2 mm (width) x 22 - 26 mm (arc length) at wafer level. The projection systems operates in scanning mode.

EUV illumination systems will in general be non-centred systems formed by off-axis segments of aspherical mirrors. The reflectivity of multilayer-coated surfaces is approximately 70 % for normal incidence and 90 % for grazing incidence. In order to maximize throughput, the number of reflections has to be minimized and grazing incidence elements should be used whenever possible.

In order to achieve the requirements of the illumination system with a limited number of optical components, the complexity of the components has to be increased. Consequently, the surfaces will be segmented or aspherical. The shape and size of aspherical mirrors and segmented elements, together with stringent requirements for the surface quality put a major challenge on manufacturing these components.

Several EUV-light sources are currently being discussed. They differ in system aspects, but also in important illuminator-related aspects. System aspects are e.g. output power, repetition rate, footprint. For the illumination system size and divergence of the radiating plasma, radiation characteristics and geometrical vignetting are relevant. The illumination design has to account for these properties.

It is well known from basic physics that the étendue is invariant in optical systems. The étendue delivered by the source has to be smaller than the étendue of the illuminator, otherwise light will be lost. For current sources, however, the étendue is approximately one order of magnitude smaller, therefore either field or pupil of the optical system is not filled completely. In addition, the ring-field with high aspect ratio requires an anmorphotic étendue, which has to be formed by the illuminator.

According to Helmholtz-Lagrange, the product of field A and numerical aperture NA is invariant in classical optical systems. For unobscured and circular pupils the Helmholtz-Lagrange-Invariant HLI or étendue can be written as:

$$(1) \qquad étendue = A \cdot \pi \cdot NA^2$$

In general, the invariance of the étendue can be interpreted as the optical equivalent to the invariance of the phase space volume in conservative

systems. The étendue can be written as a volume integral in four dimensions,

(2) $$\textit{étendue} = \int F(x, y, P_x, P_y)\, dx dy dP_x dP_y$$

with the function F describing the occupied volume in phase space and

$$\bar{P} = (n\sin\theta\cos\varphi,\ n\sin\theta\sin\varphi,\ n\cos\theta)$$

the vector of optical direction cosines, which corresponds to the pupil coordinates.

For centred systems, the optical direction cosine integration in equation (2) can be written in polar coordinates (θ, φ):

(3) $$\begin{aligned}\textit{étendue} &= \int F(x, y, \theta, \varphi)\ dA \left|\frac{\partial(P_x, P_y)}{\partial(\theta, \varphi)}\right| d\theta\, d\varphi \\ &= \int F(x, y, \theta, \varphi)\ dA \sin\theta\cos\theta\, d\theta\, d\varphi\end{aligned}$$

The illumination field at the reticle is arc-shaped with dimensions of approx. 8 mm x 88 mm. Thus the étendue to be provided by the illumination system has to be almost isotropic in angular domain, but highly anamorphotic in space domain with an aspect ration of 1:10. The different light sources, however, show an almost isotropic behaviour in space as well as in angular domain. In addition, the étendue of all known light sources is too small, although an optimum collection efficiency is assumed. In EUV illumination systems it is therefore essential to transform the étendue of the light source without changing the isotropy in angular domain. Array elements offer the

most promising methods to transform the étendue. With optical array elements the field formation with high aspect ratio as well as the filling of the required aperture can be achieved.

The étendue is not increased, but only transformed by the introduction of a segmentation in the entrance pupil. Examples for array elements are the ripple-plate (an array of cylindrical lenses) and the fly's eye-integrator. Both are capable of forming a field with high aspect ratio and introduce a segmentation in the entrance pupil. Partial coherent image simulations show that the influence of the segmentation of the pupil can be tolerated, as far as a reasonable number of segments is chosen. Illumination systems with fly's-eye integrator are described in DE 199 03 807 A1 and WO 99/57732, the content of said applications is incorporated herein by reference.

Illumination systems with ripple plates are known from Henry N. Chapman, Keith A. Nugent, "A novel Condensor for EUV Lithography Ring-Field Projection Optics", Proceedings of SPIE 3767, pp. 225 - 236, 1999.

The content of said article is also fully incorporated herein by reference.

The illumination system has to be combined with the lens system and it has to meet the constraints of the machine layout. The mechanical layout of non-centred reflective systems strongly depends on the number of mirrors and the folding angles. Within this setup, the mirrors and special components must be mounted with tight tolerances. Heat load and natural frequencies of the frame structure have to be considered.

In EUV, each reflection will suffer from 30 % light loss. The light is absorbed or dissipated leading to a heating of the mirrors. To avoid deformations of the optical elements as well as the mechanical structure, a cooling of mirrors is required. This is especially challenging because the complete optical

system has to be under vacuum and hence only conduction can be used for cooling.

Furthermore in an illumination system for lithography it is desirable to introduce means for cutting off the field e.g. by a field stop.

An illumination system for lithography with a field stop is shown in US-A-4 294 538. The content of said document is incorporated herein fully by reference. The system according to US-A-4 294 538 comprises a slit plate on which an arcuate image of the light source is formed. By varying the radial length and the length in direction of the circular arc of the opening of the slit it is possible to adjust the radial length and the length in the direction of the circular arc of the arcuate image of the light source on a mask. Therefore the slit plate can also be designated as a field stop. Between the slit plate and the mask there are two mirrors arranged for imaging the arc-shaped field in the plane of the slit plate onto a reticle-mask.

Since the illumination system known from US-A-4 294 538 is designed for a light source comprising a ultra high tension mercury lamp emitting light in the visible region the system is totally different to a illumination system for wavelengths $\leq$ 193 nm.

For example said system has no means for enhancing the étendue of the light source e.g. by raster elements of a fly's-eye integrator, which is essential for EUV-systems.

The mirrors according to US-A-4 294 538 are impinged by the rays travelling through the system under an angle of 45°, which is not possible in EUV-systems, since normal incidence mirrors in EUV-systems are comprising more than 40 pairs of alternating layers. A large number of alternating layers leads to phase effects if the mean angle of incidence becomes more than

30° or is lower than 70° . Using an angle of incidence of 45° in an EUV-system as in the state of the art would lead to a total separation of s- and p-polarisation and one of both polarisation is lost completely according to Brewster law. Furthermore such a mirror would function as a polarizing element.

Another disadvantage of the system according to US 4 294 538 are the rays impinging the reticle in the object plane telecentric, which is not possible in EUV-systems using a reflection mask.

Furthermore the system known from US-A-4 294 538 is a 1:1 system. This means that the field stop in the object plane of the imaging System has the same size as the field in the image plane. Therefore the field stop has always to be moved with the same velocity as the reticle in the image plane. Furthermore said illumination system should be applicable in high throughput systems working with much higher velocities of reticle and mask than conventional systems e.g. systems known from US-A-4 294 538.

Object of the invention is to provide an imaging system imaging an object, e.g. a field stop into an image, e.g. a reticle-mask for an illumination system for lithography with wavelengths $\leq$ 193 nm. Especially losses should be minimized, while the quality of the image especially regarding edge sharpness in scanning direction should be as high as possible.

Said object of the invention is solved in a first embodiment by a multi-mirror-system comprising an imaging system with at least a first and a second mirror, whereby said first mirror and said second mirror are arranged in the optical path of the imaging system in such a position and having such a shape, that the edge sharpness of the arc-shaped field in the image plane is smaller than 5 mm, preferably 2 mm, most preferably 1 mm in scanning direction.

In an advantageous embodiment the edge sharpness of the arc-shaped field in the image plane is smaller than 5 mm, preferably 2 mm, most preferably 1 mm also in the direction perpendicular to the scanning direction.

While the field in the image plane is always arc-shaped, in an first embodiment of the invention the object in the object plane is also an arc-shaped field; which means that the inventive imaging system is not comprising any field forming components.

Advantageously the rays travelling from the object plane to the image plane in the imaging system are impinging the first and the second mirror defining a first and a second used area on the mirrors, whereby the rays are impinging the first and the second mirror in the used area with an incidence angle relative to the surface normal of the mirror $\leq 30°$ or $\geq 60°$, especially $\leq 20°$ or $\geq 70°$, in order to minimize light losses in the system. To move the field stop in the object plane and the reticle in the image plane of the imaging system with different velocities the magnification ratio of the imaging system is unequal to 1.

In a preferred embodiment the inventive imaging system is a non centred system.

Advantageously an aperture stop is located on or close to the plane conjugate to the exit pupil of the imaging system.

Preferably the first and/or the second mirror of the imaging system is an aspheric mirror.

In a preferred embodiment of the invention the first mirror is a concave mirror having a nearly hyperbolic form or a nearly elliptic form and is defining a first axis of rotation.

Furthermore also the second mirror is a concave mirror having a nearly hyperbolic form or a nearly elliptic form and is defining a second axis of rotation.

Preferably the first and the second mirror are comprising a used area in which the rays travelling through the imaging system are impinging the first and the second mirror; the used area is arranged off-axis in respect to the first and second axis of rotation.

In advantageous embodiment the first axis of rotation and the second axis of rotation subtend an angle γ. Said angle γ is calculated from a COMA-correction of the system. The first mirror and the second mirror are defining a first magnification for the chief ray travelling through the centre of the field and the centre of the exit pupil, a second magnification for the upper COMA ray travelling through the centre of the field and the upper edge of the exit pupil and a third magnification for the lower COMA ray travelling through the centre of the field and the lower edge of the exit pupil. If the system is COMA corrected the first, the second and the third magnification are nearly identical. Said condition defines the angle γ between the first and the second axis of rotation.

In an second embodiment of the invention a multi-mirror-system for an illumination system with wavelengths $\leq$ 193 nm is comprising an imaging system, whereby said imaging system comprises at least a first mirror and a field forming optical component. In such an embodiment of the invention the field in the object plane can be of arbitrary shape, e.g. a rectangular field.

In case of a rectangular field the rectangular field is formed into an arc-shaped field in the image plane by the field forming optical component of the imaging system. The advantage of the second embodiment of the invention is the fact, that no extra optical components for forming the field in

the light path arranged before the inventive multi- mirror-system are necessary. This reduces the total number of mirrors in the illumination system and therefore the losses within the illumination system.

Preferably the aforementioned field forming component of the second embodiment comprises at least one grazing incidence mirror. Grazing incidence mirrors have the advantage that they must not be coated, whereas normal incidence mirrors in the EUV-range are always multilayer systems with high losses.

In a preferred embodiment the field forming component comprises two mirrors, a first grazing incidence mirror with positive optical power and a second grazing incidence mirror for rotating the field.

Another preferred embodiment employs a single grazing incidence field lens with negative optical power to achieve an arc-shaped field with the desired orientation.

Apart from the imaging system the invention provides an illumination system, especially for lithography with wavelengths ≤ 193 nm with a light source, a multi-mirror system comprising an imaging system, whereby the imaging system comprises an object plane. The illumination system further comprises an optical component for forming an arc-shaped field in the object plane of the multi-mirror-system, in the light path arranged before the multi-mirror system. The multi-mirror-system is a system according to the invention for imaging the field from the object plane into the image plane of the imaging system.

To enhance the étendue said illumination system could comprise at least one mirror or one lens which is or which are comprising raster elements for forming secondary light sources.

The aforementioned illumination system could be used in an EUV projection exposure unit comprising a mask on a carrier system, said mask being positioned in the image plane of the imaging system, a projection objective with an entrance pupil, said entrance pupil is situated in the same plane as the exit pupil of the illumination system and a light sensitive object on a carrier system.

Preferred embodiments of the invention are described with regard to the following figures.

In the figures are shown:

figure 1 and figure 2:	complete illumination system with an imaging system according to the invention and an arc-shaped field in the object plane of the imaging system
figure 3:	a schematic view of the inventive illumination system
figures 4 to 7:	schematic views of the inventive illumination system with abbreviation used for the derivation of the COMA correction of the system
figure 8:	detailed view of a COMA-corrected system
figure 8.1:	arc-shaped field in the image plane
figures 8.2 and 8.3:	spot diagrams of the system according to figure 8 in the image plane
figure 9:	detailed view of a system with correction of COMA, astigmatism and spherical aberration and a magnification of -1.0
figures 9.1	

to 9.2: spot diagrams of the system according to figure 9 in the image plane

figure 10: detailed view of a system with correction of COMA, astigmatism and spherical aberration of -0.85

figure 10.1 to 10.2: spot diagrams of the system according to figure 10 in the image plane

figure 11: EUV-illumination system with an inventive imaging system and a ripple plate as field forming component

figure 12: detailed view of a COMA corrected imaging system with a magnification β = - 1.5

figures 12.1 to 12.2: spot diagram of a system according to figure 12 in the image plane

figure 13: detailed view of an imaging system with a magnification β = - 1.5 and correction of COMA, astigmatism and spherical aberration

figures 13.1 to 13.2: spot diagram of a system according to figure 13 in the image plane

figure 14: schematic view of an imaging system comprising a normal and a grazing incidence mirror as field forming component

figure 15: schematic view of an imaging system comprising two normal and a grazing incidence mirror as field forming component

figure 16: view of the field in the object- and the image plane with field stop or REMA-blades

figure 17: detailed view of a system according to figure 15

figure 17.1: spot diagram of a system according to figure 17

figure 18: detailed view of a system according to figure 16

figure 18.1: spot diagram of a system according to figure 18

In figure 1 an EUV-illumination system comprising an inventive imaging system 1 comprising an object plane 3, a first mirror 5, a second mirror 7 and an image plane 9 is shown. In the object plane 3 the field stop of the system is located. Furthermore the field in the object plane 3 is already arc-shaped. The imaging system 1 images the arc-shaped field from the object plane 3 into the image plane 9. In the image plane 9 the reticle or mask of the EUV-illumination system is located. Also shown is the exit pupil 10 of the imaging system 1, which is identical with the exit pupil of the total EUV-illumination system. The exit pupil 10 falls together with the entrance pupil of the projection optical system. Furthermore the EUV-illumination system shown in Figure 1 comprises a light source 12, a collector 14, means 16 for enhancing the étendue of the light source 12 and field forming mirrors 18, 20 for forming the arc-shaped field in the object plane 3 of the imaging system 1. Also shown are a first plane 40 conjugate to the exit pupil 10 and a second plane 42 conjugate to the exit pupil 10. Furthermore the distance ePO between first field forming mirror 18 and the first plane 40 conjugated to the exit pupil 10, the distance e01 between the first 18 and the second 20 field forming mirror, the distance SE1' between the second field forming mirror 20 and the second plane 42 conjugate to the exit pupil 10, the distance SR1' between the second field forming mirror 20 and the object plane 3 and the distance SE2 between the second plane 42 conjugate to the exit pupil 10 and the first imaging mirror 5 is depicted.

Throughout the system examples shown hereinafter some parameters remain constant. The design principles as shown below however, can also be applied to other sets of parameters.

In all embodiments shown in this application the incidence angle at the image plane 9 of the imaging system is 6° and the numerical aperture at the image plane 9 is NA = 0.05. It corresponds for example to a NA = 0.0625 of the projection lens and a $\sigma = 0.8$. The projection lens arranged in the

light path after the EUV-illumination system has typically a 4x-magnification and thus NA = 0.25 at the light sensitive object e.g. the wafer of the EUV-projection exposure unit.

Figure 2 shows the EUV-illumination system depicted schematic in figure 1 in greater detail. Same components as in figure 1 are designated with the same reference numbers.

The system according to figure 2 comprises a light source 12 and a collector-mirror 14. Regarding the possible EUV-light sources reference is made to DE 199 038 07 A1 and WO 99/57732, the content of said documents is incorporated herein by reference. The collector mirror 14 of the system according to figure 2 is of elliptical shape. The means 16 for enhancing the étendue comprises two mirrors with raster elements 30, 32 so called fly-eyes integrators. The first mirror with raster elements 30 comprises an array of 4 x 64 field facets; each field facet being of plane or elliptical, toroidal or spherical shape ($R \approx -850$ mm). The second mirror with raster elements 32 comprises an array of 16 x 16 pupil facets or a spherical or hexagonal grid with pupil facets, each pupil facet being of hyperbolic, toroidal or spherical shape ($R \approx -960$ mm). The second mirror 32 is located in a plane conjugate to the exit pupil 10 of the illumination system.

An illumination system with a first and a second mirror comprising raster elements as described before is known from DE 199 038 07 A1 and WO 99/57732; the content of said applications is incorporated herein by reference.

For forming the arc shaped field in the object plane of the imaging system comprises two field forming mirrors 18, 20. The second field forming mirror 20 is a grazing incidence mirror.

In principle one mirror, here the mirror 20, would be sufficient for field forming. But mirror 18 is required to control the length of the system and the size of the pupil facets. In order to achieve a large field radius of $\approx$ 100 mm mirror 20 must have low optical power.

The size of the field and the pupil facets are related to the étendue of the system. The product of the size of the field facets and the size of the pupil plane is determined by the étendue. The pupil plane is a first plane 40 conjugate to the exit pupil 10 of the illumination system. In said plane the second mirror with raster elements 32 is located. Due to the aforementioned relation restrictions to the size of the field facets and the pupil facets are given. If the magnification for the pupil facets is very large, i.e. the pupil facet is very small, field facets become very large. To avoid large magnification of the imaging of the pupil facets into a second plane 42 conjugate to the exit pupil 10 of the system either the distance between mirror 20 and the second mirror with raster elements 32 increases or an additional mirror 18 has to be introduced. The first field forming mirror 18 has almost all power of the imaging system consisting of a first field forming mirror 18 and a second mirror 20 for imaging the pupil facets of the second field forming mirror with raster elements 32 into the second plane 42 conjugate to the exit pupil 10 of the system.

The data for the first field mirror 18 and the second field mirror 20 are given in table 1:

Table 1:

Data for the first and the second field mirror

	first field mirror 18	second field mirror 20
shape	hyperbola	ellipsoid
f	≈ 1616 mm	≈ 605 mm
incidence angle versus surface normal	7 °	75° (grazing incidence)
conic section layout	for pupil imaging	for pupil imaging
$\beta_{\text{pupil imaging}}$	7.46429	-0.05386

The magnification between the first plane 40 conjugate to the exit pupil 10 and the second plane 42 conjugate to exit pupil 10 is $\beta_{40\rightarrow 42} \approx -0.4$. The field radius of the arc-shaped field in the object plane 3 is controlled by the second field mirror 20.

If the magnification $\beta_{image} = -1$ of the imaging system and $R_{Field} = 100$ mm the field radius to be formed by the second field forming mirror 20 is $R_{Obj} = -100$ mm. There are three means to control the radius R_{Obj}: The optical power, see table 1,

f ≈ 605 mm, the chief ray distance between the second field forming mirror 20 and the object plane 3:

SR1' ≈ 250 mm and the grazing incidence angle.

With the further values for the system layout

ePO = 1400 mm

e01 = 1550 mm

SE1' ≈ 637 mm

SE2 ≈ -262.965 mm

the system can be derived with first order optical formulas.

In the second plane 42 conjugate to the exit pupil 10 an accessible aperture stop for the illumination system could be located.

Also shown in figure 2 is the inventive multi-mirror-system comprising an imaging system 1 with a first 5 and a second 7 imaging mirror for imaging the arc-shaped field from the object plane 3, which is conjugate to the field plane, into the image plane 9, which corresponds to the field plane of the illumination system and in which the reticle or mask of the illumination system is located.

The conjugate field plane 3 could be used as a plane for reticle masking. Said plane is located near to the second field forming mirror 20 at the limit for construction, e.g. SR' ≈ 250 mm chief ray distance for ≈ 15° grazing incidence reflection on the mirror. The field in the conjugate field plane which is the object plane 3 is arc-shaped by field forming mirror 20, thus rema blades need to be almost rectangular. Small distortions of a following rema system can be compensated for.

Since all mirrors of the illumination system have positive optical power, the field orientation in the conjugate field plane 3 after positive mirror 20 is mirrored by negative magnification of the inventive imaging system 1. The field orientation in the field plane 9 is then correct.

Since the second field forming mirror 20 is off-axis in order to compensate the distortion due to this off-axis arrangement, the pupil facets have to be arranged on the second mirror with raster elements 32 on a distorted grid.

With pupil facets arranged on a pre-distorted grid optimized pupils with respect to telecentricity and ellipticity can be achieved.

The derivation of a multi-mirror-system comprising an imaging system for imaging a REMA-blade situated in the object-plane or REMA-plane 3 of the inventive multi-mirror-system into the image plane or field plane 9, wherein the reticle is situated will be described in detail hereinbelow.

Figure 3 shows in a schematic refractive view the elements of the inventive imaging system and abbreviations used in table 1. Furthermore components with reference numbers used in figure 1 and 2 are designated with the same reference numbers. Furthermore in figure 3 is shown the virtual image 3' of the field plane and the virtual image 10' of the exit pupil.

The imaging system according to figure 3 and table 2 is a hyperbolic-ellipsoid combination as a first order starting system. The data of the first order system are given in table 2.

Table 2:

First order system layout

first imaging mirror 5	Hyperboloid	second imaging mirror 7	Ellipsoid
	field imaging		pupil imaging
	e23	650.0	
f	768.1818	f	650.0
Pupil imaging			
SE2	-262.9651	SE3	-1049.8383
SE2'	-399.8383	SE3'	1706.6772
$\beta 2$	1.5205	$\beta 3$	-1.6257
Field imaging			
SR2	-650.0	SR3	-4875.0
SR2'	-4225.0	SR3'	750.0
$\beta 2$	6.5	$\beta 3$	-0.15385

For the results of table 2, well-known first-order lens-formulas where used, e.g.

(4) $\beta = S'/S$

$S_{i+1} = S_i - e_{i,i+1}$

$f = 1/(1/S'-1/S)$ ("lens-maker"-equation)

where S and S' stands for SE and SE' or SR and SR', respectively.

In the next step designing an imaging system according to the invention the first order system shown in table 2 is optimized and COMA corrected.

The first mirror 5 of the imaging system is a hyperbolic mirror, optimized for field imaging, which means imaging of the field in the REMA plane 3 into the

field plane 9. The second mirror 7 of the imaging systems is an elliptical mirror optimized for pupil imaging, which means imaging of the second plane 42 conjugate to the exit pupil into the exit pupil 10. The overall system comprising the first 5 and the second 7 imaging mirror with abbreviations used in table 3 for the COMA corrected system is shown in figures 3 to 5. Identical components as in figure 1, figure 2 and figure 3 are designated with the same reference numbers.

Apart from the elements already shown in figures 1 and 2 in figure 3; figure 4 shows:

- the axis of rotation 50 of the first imaging mirror 5
- the axis of rotation 52 of the second imaging mirror 7
- the centre 54 of the first imaging mirror
- the vertex of the first imaging mirror 56
- the virtual image 3' of the field plane 3
- the centre 58 of the second imaging mirror
- the vertex of the second imaging mirror 60
- the virtual image 10' of the exit pupil 10 of the illumination system
- the chief ray 62

As is apparent from figure 4 the axis 50 of the hyperbolic mirror 5 and the axis of the elliptic mirror 7 subtend an angle γ.

Figure 5 shows in detail the first imaging mirror 5, which is in this embodiment a hyperboloid, of the inventive imaging system according to figure 4 and figure 6 the second imaging mirror 7 of the imaging system according to figure 4, which in this embodiment is a ellipse. The same elements as in figure 4 are designated in figure 5 and figure 6 with the same reference numbers.

In figure 5 depicting the first hyperbolic mirror 5 the abbreviation used for the following equations calculating the parameters of the hyperbola are known:

With positive angles ω_2 and δ_2 follows

(5) $$d_2 = -SR2 \cdot \sin(\omega_2) = -SR2' \cdot \sin(\delta_2)$$

(6) $$\omega_2 = 2\alpha_2 - \delta_2$$

$\Rightarrow$ (7) $$\beta_{field} = \frac{SR2}{SR2'} = \frac{\sin(2\alpha_2 - \delta_2)}{\sin(\delta_2)} = \frac{\sin(2\alpha_2)}{\tan(\delta_2)} - \cos(2\alpha_2)$$

$\Rightarrow$ (8) $$\delta_2 = \arctan\left(\frac{\sin(2\alpha_2)}{\beta_{field} + \cos(2\alpha_2)}\right)$$

Then the angle between incident chief ray and hyperbola axis is:

$\omega_2 = 2\alpha_2 - \delta_2$

Hyperbola equation:

(9) $$\frac{z^2}{a^2} - \frac{d^2}{b^2} = 1; \quad a = \sqrt{e^2 - b^2}$$

insertion and solution for b^2 gives:

(10) $$b^4 + (z^2 + d^2 - e^2)\, b^2 - d^2 e^2 = 0$$

$\Rightarrow$ (11) $$b^2 = \frac{-(z^2 + d^2 - e^2) + \sqrt{(z^2 + d^2 - e^2)^2 - 4 d^2 e^2}}{2}$$

with equation (5) and

(12a) $$z_2 = e + SR2 \cdot \cos(\omega_2)$$

(12b) $$e = \frac{(-SR2 \cdot \cos(\omega_2) - SR2' \cdot \cos(\delta_2))}{2}$$

the parameters defining the hyperbola can be calculated.

In figure 6 depicting the second elliptic mirror 7 the abbreviations used for the following equations calculating the parameters of the ellipse are shown:

With positive angles ω_3 and δ_3 follows

(13) $$d_3 = -SE3 \cdot \sin(\omega_3) = +SE3' \cdot \sin(\delta_3)$$

(14) $$\omega_3 = 2\alpha_3 + \delta_3$$

$\Rightarrow$ (15) $$-\beta_{pupil} = \frac{SE3'}{-SE3} = \frac{\sin(2\alpha_3 + \delta_3)}{\sin(\delta_3)} = \frac{\sin(2\alpha_3)}{\tan(\delta_3)} + \cos(2\alpha_3)$$

$$\Rightarrow (16) \qquad \delta_3 = \arctan\left(\frac{-\sin(2\alpha_3)}{\beta_{field} + \cos(2\alpha_3)}\right)$$

The angle between incident chief ray and the hyperbola axis is defined by equation (14).

Ellipsoid equation:

$$(17) \qquad \frac{z^2}{a^2} + \frac{d^2}{b^2} = 1; \quad a = \sqrt{e^2 + b^2}$$

insertion and solution for b^2 gives:

$$(18) \qquad b^4 + (e^2 - z^2 - d^2)\, b^2 - d^2 e^2 = 0$$

$$\Rightarrow (19) \qquad b^2 = \frac{-(e^2 - z^2 - d^2) + \sqrt{(e^2 - z^2 - d^2)^2 - 4 d^2 e^2}}{2}$$

with equation (13) and

$$(20a) \qquad z_3 = e - SE2 \cdot \cos(\omega_3)$$

$$(20b) \qquad e = \frac{(SE3 \cdot \cos(\omega_3) + SE3' \cdot \cos(\delta_3))}{2}$$

the parameters defining the ellipsoid can be calculated.

Furthermore for ellipse and hyperbola following equations are well known:

(21) $$p = \frac{b^2}{a}$$ curvature at node R = - p

(22) $$\varepsilon = \frac{e}{a}$$ eccentricity

(23) $$K = -\varepsilon^2$$ conic constant

By COMA-correcting the first order system according to table 2 with an analytical calculation angle γ is determined. The COMA-correction uses for calculating γ the magnification of the imaging for the chief ray 62 and the coma-rays not shown in figure 4-6. The differences in magnifications can be reduced by minimization of the angle of incidence α_3 (7°) and corresponding selection of α_2. In this example the equations are minimized by the gradient method, which means choose a start system e.g. according to table 2, calculate the magnifications, change the angle α_2 and calculate a new magnifications. From the difference in magnifications the next α_2 can be calculated. Repeat this algorithm until difference in magnification for the chief ray and the upper and lower COMA-ray is less than e.g. 0,5 %.

The COMA-correction will be described hereinbelow in detail with reference to figure 7. Identical elements as in figure 1 to 6 are designated with the same reference numbers. Furthermore in figure 7 is shown the lower COMA ray 70.

The calculation of the magnifications along the chief ray 62 is clear from the first order derivation.

The calculation for the COMA or rim rays is shown with regard to the lower COMA ray 70.

The COMA rays 70 for the imaging 3 → 3' at the hyperbola is straight forward. The COMA or rim rays in the object plane 3 can be defined by the angles between rays and hyperbola axis:

(24) $$\omega_{2c} = \omega_2 \mp arscin\left(\left| NA_{reticle} \cdot \beta_{rema,field} \right|\right)$$

with ω_2 as shown in figure 5.

The distances between the image points 3 and 3' and the intersection point I_{2c} of the mirror with the COMA or rim rays are given by hyperbola formulas in polar co-coordinates:

(25) $$S_c = \overline{RI_{2c}} = \frac{p}{1 + \varepsilon\cos(\omega_{2c})}$$

(26) $$S'_c = \overline{I_{2c}R'} = S_c + 2a$$

α, ε, p: hyperbola parameters

To calculate the lengths at the ellipse is more complicated, because the COMA or rim rays will not intersect in the plane 9 any more. However the magnification can be calculated approximately after calculating the intersection point I_{3c}. With

(27) $$\omega_{3c} = \delta_{2c} \pm \gamma$$

for given γ, ω_{3c} and thus the intersection point I_{3c} can be calculated. With

(28) $$L_c = \overline{R'\ I_{3c}}$$

(29) $$L'_c = \overline{I_{3c}R''}$$

the magnification of the rema-imaging system for the rim or COMA rays follows

(30) $$\beta_{c\pm} = \frac{L'_c}{L_c} \cdot \frac{S'_c}{S_c}$$

As shown in figure 7 this derivation is not exact, because the rim rays will not intersect in the image plane 9 exactly. However, magnification can be calculated with reasonable accuracy, sufficient for a minimisation of the COMA error.

An optimisation with the gradient method described before leads to the solution given in table 3.

Table 3:
COMA corrected system starting from the system according to table 1.

first imaging mirror 5		second imaging mirror 7	
Design parameters (abbreviation see figures 4 to 6)			
$\alpha2$	16.328°	$\alpha3$	7.0°
δ_2	4.2034	δ_3	20.26125
$\omega2$	28.4526	ω_3	34.26125
d_2 = YDE	309.6806	d_3 = YDE	591.0246
z_2	1821.0739	z_3	1234.3716
a	1787.5	a	1378.2578
b	1590.3439	b	1328.5797
e	2392.5614	e	366.7021
R	-1414.9336	R	-1280.6922
eps = e/a	1.3385	eps = e/a	0.2661
K = -eps^2	-1.7916	K = -eps^2	-0.0708
ZDE = z_2 - a	33.5616	ZDE = a - z_3	143.8861

YDE and ZDE are the y- and z-components of the decenter vector of the nearest vertex point of the conic section.

For a COMA-corrected system according to table 3 the magnification difference due to COMA is approx. 0.1 % and is identical for the upper and the lower COMA-ray. The data for the magnification β of the inventive two mirror imaging system for the chief ray, the upper and lower COMA-ray after COMA correction is shown in table 4.

Table 4:

Magnification β for chief ray, upper and lower COMA-ray

Coma-correction of Field imaging			
Upper COMA-ray		Chief ray	Lower COMA-ray
Magnification	1.0012	1.0000	1.00[illegible]2

In figure 8 the COMA-corrected imaging system is shown. Identical elements as in figures 1 to 7 are designated with the same reference numbers.

In figure 8.1 the arc-shaped field in the field or reticle plane with carthesian coordinates x and y is shown. Reference number 100 designates a field point in the centre of the arc-shaped field and 102, a field point at the edge of the arc-shaped field. The y-axis denotes the scanning direction and the x-axis the direction perpendicular to the scanning direction.

In figure 8.2 the spot diagram for a field point 100 and in figure 8.3 the spot diagram for a field point 102 of a COMA-corrected multi-mirror-system according to figures 4 to 8 is depicted. The spot diagram is the diagram resulting from a multiplicity of rays travelling through the system with the aperture NA_{object} and impinging the field or reticle plane in a predetermined

field point, e.g. the centre of the field 100. The aperture is $NA_{object} = 0.05$ in the system described in figures 4 to 8.

As is apparent from the spot-diagrams 8.2 and 8.3 the edge sharpness EDS in scanning direction, corresponding to the y-axis of the arc shaped field, in COMA corrected system is smaller than 2 mm.

The edge sharpness EDS of a system in scanning direction is defined as the difference of the points with the greatest value and the smallest value in y-direction for an edge field point, e.g. edge field point 102 as shown in figure 8.3.

For further optimizing the inventive imaging system astigmatism and spherical aberration has to be considered. Nevertheless a balanced system can be found with only hyperbolic and elliptical mirrors. Figure 9 and table 5 shows a system which is corrected for spot aberrations < 1 mm in scanning direction. Because the rema blades are essentially required to avoid the overscan in scanning direction, it is sufficient to achieve the required performance in scanning direction; here in y-direction.

In figure 9 the same elements as in figures 1 to 8 are designated with the same reference numbers. In figure 9.1 and 9.2 the spot-diagrams for a point in the centre of the field 100 and for an edge point 102 is depicted.

The optical data of the system according to figure 9 are shown in table 5.

The embodiment according to figure 9 is again a 1:1 imaging system and is derived from the embodiment according to figure 8.

Table 5:

System corrected for COMA, astigmation and spherical aberration

first imaging mirror 5	Hyberbola	second imaging mirror 7	Ellipse
α_2	8.9395	α_3	6.4304
δ_2	1.9988	δ_3	20.5977
ω_2	15.8802	ω_3	33.4585
d_2 = YDE	283.1433	d_3 = YDE	587.5428
a2	5949.4780	a3	1371.5001
b	2942.2505	b	1329.5276
e	6637.2529	e	336.7028
R	-1455.0585	R	-1268.8396
eps = e/a	1.1156	eps = e/a	0.2455
K = -eps^2	-1.2446	K = -eps^2	-0.0603
ZDE	29.4941	ZDE	143.7641

The image plane 9 comprising the reticle is tilted with respect to the chief ray by 6°-angle of incidence. For a minimized spot aberration also the object plane 3 has to be tilted. In the example the optimized tilt angle of the object plane 3, where the field stop or rema has to be placed, is approximately 0.9768°.

Also shown in figures 8 and 9 are the complete first hyperbolic imaging 5 and the complete second elliptic imaging mirror 7 of the imaging system with the first axis of rotation 50 and the second axis of rotation 52. As is apparent from figure 9 the rays impinging the mirrors of the imaging system off-axis; this means that the used area of the two mirrors are situated off-axis with regard to the axis of rotation of the two mirrors. Also clearly shown the angle γ between the two axis of rotation.

In figure 10 an even better performing imaging system than the system according to figure 8 is shown. The same reference numbers as for the system according to figure 9 are used. The system according to figure 10 is derived from a more balanced optimization. This time the magnification is $\beta \approx -0{,}85$.

The limiting aberrations in the imaging system according to the invention is COMA and astigmatism.

For field imaging a mirror 5 near to conjugate pupil plane 42 is used. This mirror 5 is aimed not to affect pupil imaging. If one looks at the aberrations in a plane which contains the focus, for field points different from the focus there are field aberrations. That is the case of the hyperbola, which is actually limited by astigmatism. For a given field of view size the smaller the tilt angle of the hyperbola, the smaller the angle of the field objects and, therefore, the smaller the astigmatism.

An elliptical mirror 7 is chosen for pupil imaging. The ellipse case is more complicated because the parameters are found to give stigmatic imaging at the centre of the exit pupil, not in the field plane 7. When used off axis for other conjugates different than the two geometrical foci, the ellipse introduces coma, and this is what can be seen in the field plane 7. Once more, the way of reducing this coma is minimising the tilt and balancing COMA between the first mirror 5 and the second mirror 7 of the imaging system.

The spot diagrams for the centre field point 100 and an edge field point 102 for a system according to figure 10 are depicted in figures 10.1 and 10.2. As is apparent from figure 10.2 the edge sharpness EDS for an edge field point is better than 1 mm in the scanning direction as well as in the direction perpendicular to the scanning direction. Said embodiment is a prefered

embodiment since the required imaging performance of the imaging system is also achieved in the direction perpendicular to the scanning direction; here in the x-direction.

The data of the system according to figure 10 are given in Code-V-format in table 6.

Table 6:

Code V-table of a imaging system with β = - 0.85

!	Radius	distance to next surface	Surface typ			
S0	0	0	DAR;	ADE	6,0;	
S	0	-369.481	REFL			
S	0	-110.093				
S	6964.67	0	REFL	!	**first imaging mirror 5**	
	CON					
	K	-205.127				
	DAR;			ADE	-19.23631;	
			YDE	149.7571;	ZDE	50.40653
S	0	0				
				ADE	-36.0;	
S	0	500.9524				
S	0	0				
				ADE	10.0;	
S	-898.3867	0	REFL	!	**Second imaging mirror 7**	
	CON					
	K	-0.2302684				
	DAR;			ADE	5.464502;	
			YDE	164.4807;	ZDE	-0.638
	CIR	1000				
S	0	-797				
S	0	0	REFL			
	BEN;			ADE	-6.0;	
	CIR	500				
SI	0	0		!Reticle		
	DAR			ADE	6.0	

In figure 11 a EUV-illumination system with a ripple-plate 200 as field-forming component and an multi-mirror-system comprising an imaging system 1 according to the invention is shown. The system comprising a light source 12, a collector unit 14, a ripple-plate 200 as a field-forming component for the arc-shaped field and a field mirror (202) is known from Henry N. Chapman et al. a.a.O; the content of said article is incorporated herein by reference.

The imaging system shown in figure 11 is identical to the imaging systems according to figures 1 to 10. The same elements as in figures 1 to 10 are designated with the same reference numbers.

Other setups then those of figure 11 are possible, in which the light is not collimated before the ripple plate 200, but converging to a focal point. In this case the grooves of the ripple plate are not parallel, but conically, i.e. the prolongation of the grooves meet in one point corresponding to the focal point of the incident wave.

The shape of the ripple plate 200 can be derived theoretically, but has to be optimized. The pupil formation with the ripple design leads to an elliptical illumination of the exit pupil after the illumination system corresponding to the entrance pupil of the lens system. Therefore an aperture stop is required in a conjugate pupil plane. This aperture stop will also lead to light loss. The ellipticity of the pupil increases with the lateral coordinate, along the arc field perpendicular to scanning direction. The light loss has to be compensated for by shaping the ripple plate aspherically.

Next, two examples of hyperbola - ellipsoid-combinations for the imaging mirrors 5, 7 are shown with β = -1.5. The first order system is analytically derived, as described before. The second system is optimized for a better

performance in scanning direction. The parameters are given in tables 7 to 9:

Table 7: First-order parameters for β_{rema} = -1.5 - system.

first imaging mirror 5	Hyberboloid	second imaging mirror 7	Ellipsoid
	e 23	650.00	
f_2	495.9484	f_3	721.5351
pupil imaging			
SE2	-271.5174	SE3	-1250.0000
SE2'	-600.0000	SE3'	1706.6772
β_2	2.2098	β_3	-1.3653
field imaging			
SR2	-482.9048	SR3	-19011.2108
SR2'	-18361.2108	SR3'	750.0000
β_2	38.0224	β_3	-0.0395

If one corrects the coma of the system of table 7 according to analytic solution of ellipsoid and hyperboloid, as shown before, a system as shown in table 8 and figure 12 results. The spot aberrations are shown in figure 12.1 and figure 12.2 for a centre field point 100 and an edge field point 102.

<u>Table 8:</u> COMA corrected system

first imaging mirror 5		second imaging mirror 7	
α_2	8.4600	$\alpha 3$	6.5000
δ_2	0.4278	δ_3	29.9146
ω_2	16.4922	ω_3	42.9146
d_2 = YDE	137.04894	d_3 = YDE	851.1340
α_2	8939.1530	α_3	1478.3386
b	2945.3024	b	1441.2091
e	9411.8682	e	281.9172
R	-970.4282	R	-1424.5774
eps = e/a	1.0529	eps = e/a	0.1907
K = -eps^2	-1.1086	K = -eps^2	-0.0364
ZDE = z-a	9.9779	ZDE= a-z	280.9593

The embodiment according to figure 13 and table 9 is optimized to achieve spot aberration less than 1 mm in scanning direction:

<u>Table 9:</u> Optimized design

first imaging mirror 5		second imaging mirror 7	
α_2	8.0302	α_3	6.2127
δ_2	0.1706	δ_3	30.3800
ω_2	16.2310	ω_3	42.8054
d = YDE	139.9744	d = YDE	848.9438
R	-967.1380	R	-1415.0130
K = -eps^2	-1.1933	K = -eps^2	-0.04913
ZDE = z-a	11.3839	ZDE= a-z	284.2995

In the following section an illumination system with an arbitrary field, e.g. a rectangular field in the object plane 3 is discussed. The schematic set-up for such systems are shown in figures 14 and 15. In both examples the imaging system images a rectangular field 300 into an arc-shaped field 302. Consequently arc-shaped rema blades or field stop 304 have to be applied to compensate for the deformation induced by the imaging with grazing incidence field mirror 306 as shown in figure 16. Furthermore in figure 16 the clipping 308 in the image or rema-plane 9 is shown.

The system according to figures 14 and 15 comprises: an object plane 3 at least, a first imaging normal incidence mirror 5 and at least one grazing incidence mirror 306 for forming the arc-shaped field in the imagine plane 9.

A realisation of a system with one grazing incidence mirror 306 is given in figure 17. To achieve the desired orientation for the ring field, a field lens with negative optical power is required. The radius of the arc-shaped field is approximately 138 mm, however, by the angle of incidence and the optical power of the first imaging mirror 5 almost any desired field radius is achievable. Table 10 gives the data for such a system, where for the magnification β_{image} = -1.2 was chosen.

Table 10:

first imaging mirror 5	ellipsoid	second imaging mirror 7	hyperboloid
α_1	12.0	α_2	78.0
	e 23	500.00	
f_1	382.1450	f_2	-868.3020
field imaging			
SE1	-609.7360	SE2	523.8000
SE1'	1023.8000	SE2'	1320.2146
β_1	-1.6791	β_2	2.5205
pupil imaging			
SR1	-810.6258	SR2	222.9651
SR1'	722.9651	SR2'	300.0000
β_1	-0.8919	β_2	1.3455
surface parameters			
δ_1	27.9820	δ_2	14.2042
ω_1	51.9820	ω_2	38.2042
e	264.2854	e	434.1220
d	480.3602	d	323.9526
b	772.8280	b	172.8956
a	816.7680	a	398.2073
p = R	-731.2519	p = R	75.0687
eps	0.3236	eps	1.0902
K	-0.1047	K	-1.1885
z	639.8277	z	845.7300

The arcuate field is demonstrated in figure 17.1. A rectangular aperture was ray-traced through the system until the reticle plane. Here the arc-shaped field arises due to the grazing incidence reflection at the grazing incidence

mirror 306. However, the spot diameter is in this un-optimized example about 10 mm. Due to the imaging with one normal incidence and one grazing incidence mirror, a large amount of coma is introduced, which can not be reduced effectively.

A reduction of coma is possible by insertion of a second normal incidence mirror 7. An example is shown in figure 18, the corresponding data are given in table 11 (with β_{image} = -1.272). The illumination at reticle field is shown in figure 18.1. The system has capability to be optimized further to similar performance as system examples given before by similar straight forward optimization, which means proper selection of reflection and folding angles.

Table 11:

first imaging mirror 5	ellipsoid	second imaging mirror 7	hyperboloid	grazing incidence mirror	hyperboloid
α_0	8.0	α_1	11.0	α_2	12.0
	e 01	450.0000	e12	500.000	
f_0	686.2745	f_1	1055.0641	f_2	-888.302
pupil imaging					
SE0	-700.0360	SE1	3455,9	SE2	523.8
SE0'	35000.0	SE1'	1023.8	SE2'	1320.2146
β_0	-50.0	β_1	0.0296	β_2	2.5205
field imaging					
SR0	-914.8405	SR1	2296.8290	SR2	222.9651
SR0'	2746.8290	SR1'	722.9651	SR2'	300.0
β_0	-3.0025	β_1	0.3148	β_2	1.3455
δ_0	7.6903	δ_1	21.3810193242	δ_2	14.2042
ω_0	23.6903	ω_1	0.6189806758	ω_2	38.2042
b	1569.789	b	5838.1891964484	b	172.8956
a	1830.8348	a	16763.1000000000	a	398.2073
p = R	-1345.9639	p = R	-2033.3024973619	p = R	-75.0687
eps	0.5146	eps	1.0589128053	eps	1.0902
K	-0.2448	K	-1.1212963293	K	-1.1885
e	942.1881	e	17750.6612469375	e	434.122
d	367.5763	d	373.24505478583	d	323.9526
z	1779.9358	z	-16797.3226034857	z	845.73

Reference numbers:

1: imaging system
3: object plane = field plane
3': virtual image of the field plane
5: first imaging mirror
9: image plane
10: exit pupil
10': virtual image of the exit pupil
12: light source
14: collector
16: means for enhancing the entendu
18: first field forming mirrors
20: second field forming mirrors
30: first mirror with raster elements
32: second mirror with raster elements
40: first plane conjugate to the exit pupil
42: second plane conjugate to the exit pupil
50: axis of rotation of the first imaging mirror
52: axis of rotation of the second imaging mirror
54: centre of the first imaging mirror
56: vertex of the first imaging mirror
58: centre of the second imaging mirror
60: vertex of the second imaging mirror
62: chief ray
70: lower COMA ray
100: field point in the centre of the arc shaped field
102: field point at the edge of the arc shaped field
200: ripple plate
300: rectangular field
302: arc shaped field

304: field stop

306: grazing incidence mirror

308: clipping

ePO: distance between first mirror and first plane conjugate to the exit plane

e01: distance between first and second field forming mirror

EDS: edge shapness

SE1': distance between second field forming mirror and second plane conjugate to the exit pupil

SR1': distance between second field forming mirror and object plane

SE2: distance between second plane conjugate to the exit pupil and first imaging mirror

x: direction perpendicular to the scanning direction

y: direction in scanning direction

γ: angle between the axis of rotation 50, 52

f_i: focal length of optical component i

α_i: angle of incidence of chief ray with respect of surface normal of mirror i

β_{pupil}: magnification for pupil imaging between conjugate pupil planes

β_{field}: magnification for field imaging between conjugate field plane and reticle plane

β_i: magnification for the intermediate imaging at a single optical element, either for pupil or for field imaging (depending on context)

R: field radius

S: working distances

SEi: working distance with respect to entrance pupil imaging between mirror i on object side

SEi': working distance with respect to entrance pupil imaging between mirror i on image side

SRi: working distance with respect to field imaging between mirror i on object side

SRi': working distance with respect to field imaging between mirror i on image side

eij: distance between optical element i and j

ω_i: angle between incident chief ray and rotation axis of optical element i

δ_i: angle between reflected chief ray and rotation axis of optical element i

a,b,e,

ε,p,K: conic section parameters for individual mirror

d_i: transversal co-ordinate of intersection point of chief ray with mirror i with respect to rotation axis

z_i: longitudinal co-ordinate of intersection point of chief ray with mirror i with respect to centre of conic section

$\beta_{c\pm}$: magnification for upper or lower coma or rim rays

YDE,

ZDE: decenter vector components as usual in optical design programs (e.g. CODE V).